

## ESTIMATED SHUTTLE LOADING EMISSIONS

by

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### ABSTRACT

As Space Shuttle tanks are loaded with  $\text{N}_2\text{O}_4$ , pressurization gas is displaced and at the same time  $\text{N}_2\text{O}_4$  entering the tank evaporates and mixes with the pressurization gas remaining in the tank. Further addition of  $\text{N}_2\text{O}_4$  to the tank requires venting of this mixture of  $\text{N}_2\text{O}_4/\text{NO}_2$  vapor and pressurization gas, which must be scrubbed prior to atmospheric release.

A computer analysis was performed to estimate concentrations, flow rates, and total quantities vented during the planned fast fill/slow fill cycles of 125 gallon and 640 gallon Space Shuttle tanks. With helium as the pressurization gas, total vent quantities were estimated to be 4.5 and 24 pounds  $\text{N}_2\text{O}_4$ , respectively, for the two tank sizes.

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## 1. STATEMENT OF THE PROBLEM

The functional parameters pertinent to Space Shuttle hypergol loading operations are given in Table I. Essentially we are concerned with two types of tank for each propellant: 125 gallon tanks that are fast filled at 35 psig and then slow filled at a pressure that rises to 125 psig and stays there, and 640 gallon tanks that are fast filled and slow filled at 35 psig.

TABLE I

Hypergol System Functional Parameters

| Orbital System | Propellants On-Board (Gallons) |                               | Flowrate (GPM)     |                       | Ullage Pressure (PSIG) |           |
|----------------|--------------------------------|-------------------------------|--------------------|-----------------------|------------------------|-----------|
|                | MMH                            | N <sub>2</sub> O <sub>4</sub> | Fast Fill<br>0-90% | Slow Fill<br>90%-100% | Fast Fill              | Slow Fill |
| FRCS           | 125                            | 125                           | 10                 | 2                     | 35                     | 125       |
| LH ARCS        | 125                            | 125                           | 10                 | 2                     | 35                     | 125       |
| RH ARCS        | 125                            | 125                           | 10                 | 2                     | 35                     | 125       |
| LH OMS         | 640                            | 640                           | 60                 | 10                    | 35                     | 35        |
| RH OMS         | 640                            | 640                           | 60                 | 10                    | 35                     | 35        |
| PBK            | 3x640                          | 3x640                         | 60                 | 10                    | 35                     | 35        |

Assume that we start with a propellant tank full of helium at 35 psig, 70°F, and begin to flow liquid propellant into the tank at a constant rate. As the first propellant enters, evaporation occurs, and liquid continues to evaporate as the tank fills until the gas over the propellant is saturated. At the same time, the vent is open and propellant vapor and pressurization gas are removed from the tank at a rate sufficient to maintain the desired ullage pressure. An estimate of the total quantity of propellant vapor discharged through the vent, as a function of time, is required.

## 2. FIRST APPROXIMATION

A very simple analysis may be performed by assuming that the mass of propellant vented is simply equal to the mass of saturated propellant vapor that will completely fill the tank minus the amount in the ullage at the end:

$$m_{p.v.} = \frac{p_{sat} (V - V_{ull})}{R_p T}$$

where  $V$  is the total tank volume,  $V_{ull}$  the final ullage volume,  $T$  the temperature of the gas mixture, and  $R_p$  and  $p_{sat}$  the gas constant and saturation pressure for the propellant in question. This approximation is based on a simplified model in which the tank is assumed to fill instantly with saturated vapor — without any venting being required — and then the saturated vapor is steadily pushed out the vent by the entering propellant. No further evaporation occurs because of the saturation condition.

Saturation pressure of  $N_2O_4$  at 70°F is 14.71 psia, and the molecular weight (corrected for dissociation to  $NO_2$ , assuming an equilibrium mixture of  $N_2O_4 - NO_2$  at 70°F, 35 psig) is 87.82, giving  $R_p = 17.597$  ft-lbf/lbm - °R. We are concerned with two tank sizes:  $(V - V_{ull}) = 125$  gal and 640 gal. The results are:

125 Gallon  $N_2O_4$  Tank:

$$m_{p.v.} = \frac{(14.71) (144) (125) (.1337)}{(17.597) (529.67)} = 3.798 \text{ lbm}$$

640 Gallon  $N_2O_4$  Tank:

$$m_{p.v.} = \left( \frac{640}{125} \right) (3.798) = 19.45 \text{ lbm}$$

It should be noted that these calculations do not take account of the increased pressures during the last 10% of fill of the 125 gallon tanks. In the actual fill, the vent would close for a period of time to allow pressure to increase, and hence the quantity vented would be less than that calculated. After compression, the ullage gas still contains the same amount of propellant, but it is less than saturated because of increased temperature. No further evaporation occurs, however, because the liquid propellant is still at 70°F and its vapor pressure is now less than the partial pressure of the propellant in the compressed ullage.

Beyond this consideration, however, it is not possible to ascertain whether this model is conservative or not. It has a conservative aspect, in that the gas being vented always contains the maximum possible concentration of propellant. It also has an anti-conservative aspect, in that the gas flow rate out of the tank is always taken to be its lowest possible value — equal to the volume flow rate of liquid into the tank. Any time evaporation is occurring, the volume flow of gas out of the tank must exceed the liquid volume flow in — a fact not taken into account by this always-saturated approximation.

Because of the fact that evaporation of the propellant in the tank might cause the results found above to be substantially too low, a more careful analysis was undertaken. This analysis is best described as a "second approximation," however, for reasons discussed later. It represents a preliminary estimate of the vent propellant quantities.

### 3. SECOND APPROXIMATION

#### 3.1 Formulation

At any point in time, the volume occupied by gas in the tank is decreasing due to the addition of liquid to the tank, corrected by the amount of liquid that is evaporating:

$$\frac{dV}{dt} = - \left( \dot{Q}_{in} - \frac{\dot{m}_{evap}}{\rho_{liq}} \right) \quad (1)$$

where

$V(t) =$  Tank ullage volume

$\dot{Q}_{in} =$  Volume flow rate of liquid into the tank

$\dot{m}_{evap} =$  Rate at which liquid is evaporating, mass per unit time

$\rho_{liq} =$  Liquid density

The volume flow of gas out the vent is equal to the rate at which the ullage volume is decreasing, plus a term to account for the generation of gas due to evaporation. We assume that the temperature and pressure of the gas mixture remain constant during evaporation, and that both components act as perfect gases. Consider a system composed of the gas molecules near the liquid-gas interface, with new molecules entering the system as liquid evaporates and no molecules leaving the system. This system will therefore be expanding. Its total volume can be treated as the sum of the partial volumes of each component gas because of the perfect gas assumption; the partial volume of the helium is constant (constant mass, temperature, and mixture pressure), while the partial volume of the propellant increases because of mass addition:

$$V_p = M_p R_p T/p$$

$$\frac{dV_p}{dt} = \dot{m}_{evap} R_p T/p$$

where

|       |  |
|-------|--|
| $V_p$ | = partial volume of propellant vapor     |
| $m_p$ | = mass of propellant vapor in the system |
| $R_p$ | = gas constant for the propellant vapor  |
| $T$   | = mixture temperature                    |
| $p$   | = mixture pressure                       |

Since the partial volume of the helium is constant, the total volume of this system is increasing at a rate given by  $dV_p/dt$ . This term is added to the rate at which the ullage volume is shrinking to give the volume flow of gas out the vent:

$$\dot{Q}_{out} = - \frac{dV}{dt} + \dot{m}_{evap} R_p T/p \quad (2)$$

The portion of this volume flow that is propellant vapor varies with time because of the non-uniform distribution of propellant vapor in the ullage. Since the vent is the farthest point in the tank from the evaporating liquid surface, the propellant vapor concentration there should always be less than or equal to the average (uniform distribution) concentration, and hence a conservative result will be obtained

by assuming a uniform distribution of propellant vapor in the tank at all times. With this assumption, the density of propellant vapor at the vent is

$$\rho_p = \frac{p_p}{R_p T} \quad (3)$$

where the partial pressure of the propellant vapor, which the assumption says is uniform, is given by

$$p_p = m_p R_p T / V, \quad (4)$$

$m_p$  being the total mass of propellant vapor contained in the ullage. The mass flow of propellant out the vent is the product of the total volume flow at the vent and the propellant vapor density at the vent:

$$\dot{m}_{p_{out}} = \dot{Q}_{out} \rho_p \quad (5)$$

Finally, we have a continuity equation which provides a second relation between  $\dot{m}_{p_{out}}$  and  $m_p$ :

$$\frac{dm_p}{dt} = \dot{m}_{evap} - \dot{m}_{p_{out}} \quad (6)$$

Equations (1) through (6) constitute 6 equations - including first order differential equations - for the 6 unknown functions of time,  $V$ ,  $\dot{Q}_{out}$ ,  $\rho_p$ ,  $p_p$ ,  $m_p$ , and  $\dot{m}_{p_{out}}$ , in terms of the parameters  $\dot{m}_{evap}$ ,  $\dot{Q}_{in}$ ,  $\rho_{liq}$ ,  $T$ ,  $p$ ,  $R_p$ .

Equations (2) through (6) are readily combined:

$$\begin{aligned} \frac{dm_p}{dt} &= \dot{m}_{evap} - \dot{Q}_{out} \rho_p \\ &= \dot{m}_{evap} - \left( -\frac{dV}{dt} + \dot{m}_{evap} \frac{R_p T}{p} \right) \left( \frac{m_p}{V} \right) \\ &= \dot{m}_{evap} \left( 1 - \frac{m_p}{V} \frac{R_p T}{p} \right) + \frac{m_p}{V} \frac{dV}{dt} \quad (7) \end{aligned}$$

Equations (1) and (7) now constitute two first order differential equations for the two unknowns  $m_p$  and  $V$ ; for solution, two initial conditions will also be required.

Before looking at the initial conditions, we should examine  $\dot{m}_{evap}$  more closely. Evaporation is expected to be maximum when there is no propellant vapor. For the purpose of this analysis, then, we assumed  $\dot{m}_{evap}$  to be given by an equation of the form

$$\dot{m}_{\text{evap}} = A \left( \frac{p_{\text{sat}}(T)}{p_p} - 1 \right)$$

where

$p_{\text{sat}}(T)$  = saturation pressure for the propellant

$A$  = "Evaporation rate coefficient" defined by this equation

Substituting this expression into equations (1) and (7), with  $p_p$  given by (4), results in

$$\frac{dV}{dt} = - \left( \dot{Q}_{\text{in}} - \frac{A}{m_p R_p T} \left( \frac{p_{\text{sat}} V}{m_p R_p T} - 1 \right) \right) \quad (8)$$

$$\frac{dm_p}{dt} = A \left( \frac{p_{\text{sat}} V}{m_p R_p T} - 1 \right) \left( 1 - \frac{m_p R_p T}{p V} \right) + \frac{m_p}{V} \frac{dV}{dt} \quad (9)$$

### 3.2 Initial Conditions

Two initial conditions are required. One condition,  $V=V_{\text{tank}}$  at  $t=0$ , is quite straightforward. If we try to apply the condition  $m_p=0$ ,  $t=0$ , however, there is an obvious problem with equation (9). This problem can be resolved by considering that as  $t \rightarrow 0$ ,  $m_p \rightarrow 0$  and  $p_p \rightarrow 0$ , and therefore

$$\dot{m}_{\text{evap}} \rightarrow A \frac{p_{\text{sat}}(T)}{p_p} = A p_{\text{sat}}(T) / (m_p R_p T / V_{\text{tank}})$$

so that with

$\dot{Q}_{\text{out}} = 0$  at  $t=0$ , we have:

$$\lim_{t \rightarrow 0} \left( \frac{dm_p}{dt} \right) = \frac{A p_{\text{sat}} V_{\text{tank}}}{m_p R_p T}$$

which can be readily integrated to give

$$\lim_{t \rightarrow 0} (m_p) = \left( \frac{2A p_{\text{sat}} V_{\text{tank}}}{R_p T} t \right)^{1/2} \quad (10)$$

which can be applied at some small finite time  $\delta t$ , and hence is quite appropriate for the finite difference method of solution that will be applied to obtain the simultaneous solution of equations (8) and (9).

There are two limitations on the initial  $m_p$  that must also be considered:

1. The initial  $m_p$  cannot exceed the total propellant mass that has entered the tank in the initial time step  $\delta t$ ,

$$m_p \leq \dot{Q}_{in} \rho_{liq} \delta t \quad (10')$$

2. The initial  $m_p$  cannot exceed the mass of propellant present when the tank is full of saturated vapor,

$$m_p \leq \frac{p_{sat}(T) V}{R_p T} \quad (10'')$$

### 3.3 Slow Fill Analysis

The slow fill presents no problems in the 640 - gallon tanks, where the fill and outflow rates simply decrease after 90% loading with no change in ullage gas properties. In the 125-gallon tanks, however, the vent closes for a period while the pressure increases.

During the vent-closed period, we assume that the gas undergoes an isentropic compression, with no evaporation or condensation occurring. We further assume that it is a perfect gas with constant specific heats. These assumptions yield the equations

$$V_2 = V_1 \left( p_1/p_2 \right)^{1/\gamma} \quad (11)$$

$$T_2 = T_1 \left( p_2/p_1 \right)^{\frac{\gamma-1}{\gamma}} \quad (12)$$

for final volume and temperature,  $V_2$  and  $T_2$ , in terms of volume  $V_1$ , temperature  $T_1$ , and pressure  $p_1$  at the beginning of the compression, and final pressure  $p_2$ .  $\gamma$  is the ratio of specific heats, which for a mixture of perfect gases can be expressed as

$$\gamma = \frac{\sum_i p_i \hat{c}_{pi}}{\sum_i p_i \hat{c}_{vi}} \quad (13)$$

where

- $p_i$  = partial pressure of the  $i^{th}$  component
- $\hat{c}_{pi}$  = the molal specific heat at constant pressure of the  $i^{th}$  component
- $\hat{c}_{vi}$  = the molal specific heat at constant volume of the  $i^{th}$  component



At standard temperature and low pressure, the specific heats have the following values:

$$\text{Helium} \quad c_p = 5.00 \quad \text{Btu/lb mole} - ^\circ\text{R}$$

$$c_v = 3.000 \quad \text{Btu/lb mole} - ^\circ\text{R}$$

$$\text{N}_2\text{O}_4^1 \quad \hat{c}_p = (.2033) (87.82) \text{ cal/gmole} - ^\circ\text{K}$$

$$\hat{c}_v = \hat{c}_p - R = [(.2033) (87.82) - 1.986] \text{ cal/gmole} - ^\circ\text{K}$$

It should be noted that in the case of  $\text{N}_2\text{O}_4$ , the frozen equilibrium heat capacity was chosen as being the only one consistent with the perfect gas assumption. The equilibrium molecular weight at  $70^\circ\text{F}$  (87.82) was used in the equations above to obtain the molal heat capacity from Fan and Mason's value of .2033 cal/gram -  $^\circ\text{C}$ .

Partial pressure of the  $\text{N}_2\text{O}_4$  vapor is given by equation (4) above. Helium partial pressure is found by subtracting the appropriate propellant vapor partial pressure from the tank pressure. The resultant ratio of specific heats, equation (13), is:

$$\gamma_{\text{N}_2\text{O}_4 \text{ tank ullage}} = \frac{(.2033) (87.82) p_{\text{N}_2\text{O}_4} + 5.00 (p - p_{\text{N}_2\text{O}_4})}{[ (.2033) (87.82) - 1.986 ] p_{\text{N}_2\text{O}_4} + 3.000 (p - p_{\text{N}_2\text{O}_4})} \quad (13')$$

If we use the saturation pressure at  $70^\circ\text{F}$  for the  $\text{N}_2\text{O}_4$  vapor partial pressure, we obtain the value

$$\gamma_{\text{N}_2\text{O}_4 \text{ ullage}} = 1.293$$

and substituting this value into equations (11) and (12), with

$$V_1 = 17.91 \text{ ft}^3 - (.90) (125 \text{ gal}) (.1337 \text{ ft}^3/\text{gal})$$

$$= 2.869 \text{ ft}^3$$

$$T_1 = 70^\circ\text{F} = 529.67^\circ\text{R}$$

$$p_1 = 35 \text{ psig} = 49.7 \text{ psia}$$

$$p_2 = 125 \text{ psig} = 139.7 \text{ psia}$$

gives the results:

$$\frac{V_2}{\text{N}_2\text{O}_4 \text{ ullage}} = 2.869 \left( \frac{49.7}{139.7} \right) \frac{1}{1.293} - 1.290 \text{ ft}^3$$

1. Fan, Stephen S. T., and David M. Mason, "Properties of the System  $\text{N}_2\text{O}_4 \rightleftharpoons 2\text{NO}_2 \rightleftharpoons 2\text{NO} + \text{O}_2$ ." J. of Chem and Eng. Data, Volume 7, pp. 183-186 (April 1962).

$$\begin{array}{c} T_2 \\ \text{N}_2\text{O}_4 \\ \text{ullage} \end{array} = 529.67 \left( \frac{139.7}{49.7} \right)^{\frac{.293}{1.293}} = 669.4^\circ\text{R} = 210^\circ\text{F}$$

From these results we deduce two important facts:

1. Since the final ullage volume in the 125 gallon tanks is

$$17.91 - (125) (.1337) = 1.20 \text{ ft}^3$$

maximum pressure will be reached before the tank is "full", and the vent will re-open to release some gas at 125 psig.

2. The saturation pressure of an equilibrium mixture of  $\text{N}_2\text{O}_4$  and  $\text{NO}_2$  calculated for  $210^\circ\text{F}$  is 14,920 mm Hg or 288.4 psia, and since the actual partial pressure of this constituent will increase in proportion to the tank pressure, the final partial pressure is well below saturation, and hence condensation at the relatively cool liquid and solid surfaces, although it will occur, can probably be neglected.

### 3.4 Numerical Solution

Equations (8) and (9) were written as difference equations:

$$\Delta V = - \left( \dot{Q}_{\text{in}} - \frac{A}{\rho_{\text{liq}}} \left( \frac{P_{\text{sat}} V}{m_p R_p T} - 1 \right) \right) \Delta t \quad (14)$$

$$\Delta m_p = A \left( \frac{P_{\text{sat}} V}{m_p R_p T} - 1 \right) \left( 1 - \frac{m_p R_p T}{p V} \right) \Delta t + \frac{m_p}{V} \Delta V \quad (15)$$

and solved incrementally; that is, at each time step, the changes in  $V$  and  $m_p$  were calculated using the values of  $V$  and  $m_p$  calculated at the preceding time step. Initial values of  $V$  and  $M_p$  were found as described in Section 3.2.

Values used were the following:

$$\begin{array}{ll} p &= 7156 \text{ lbf/ft}^2 \\ T &= 529.67^\circ\text{R} \\ \Delta t &= 1.0 \text{ sec} \\ \rho_{\text{liq}} &= 90.35 \text{ lbm/ft}^3 \\ P_{\text{sat}} &= 2118.24 \text{ lbf/ft}^2 \\ R_p &= 17.597 \text{ ft} \cdot \text{lbf/lbm} \cdot ^\circ\text{R} \\ \hat{c}_p &= 17.85 \text{ cal/mole} \cdot ^\circ\text{K} \end{array}$$

Calculations were performed, in all cases, for five values of the "evaporation rate coefficient" defined on page 9:

$$A = .01, .1, 1.0, 10.0, 100.0 \text{ lbm/sec}$$

(The effect of varying surface area on evaporation rates was not taken into account). The following sets of values were used for the two tank

| sizes:     | Initial<br>$V_{\text{tank}}$ | Final<br>Propellant<br>Volume (liq) | $(\dot{Q}_{\text{in}})_{\text{fast}}$ | $(\dot{Q}_{\text{in}})_{\text{slow}}$ |
|------------|------------------------------|-------------------------------------|---------------------------------------|---------------------------------------|
| Small tank | 17.91 ft <sup>3</sup>        | 125 gal                             | 10 gal/min                            | 2 gal/min                             |
| Large tank | 89.5 ft <sup>3</sup>         | 640 gal                             | 60 gal/min                            | 10 gal/min                            |

The procedure was as follows:

1. For the initial time step, an average mass was calculated using equation (10). The average was found in the usual way,

$$\begin{aligned}
 (m_p)_{\text{ave}} &= \frac{1}{\Delta t} \int_0^{\Delta t} m_p(t) dt \\
 &= \frac{4}{3} \left( \frac{A P_{\text{sat}} V_{\text{tank}}}{R_p T} \Delta t \right)^{1/2}
 \end{aligned}$$

2. The limiting value of  $m_p$  from eqn (10') was calculated and compared to the preceding value. If smaller, it replaced it.
3. The limiting value of  $m_p$  from eqn (10'') was calculated and compared to the preceding value. If smaller, it replaced it.
4. Outflows for the first time step were calculated using the resultant value of  $m_p$ .
5. Volume and mass increments were calculated from equations (14) and (15) using these initial values of  $V$  and  $m_p$ , and used to find new values of  $V$  and  $m_p$ .
6. This finite difference procedure was continued until either the ullage was saturated with propellant vapor, or the liquid volume in the tank reached 90% of its final value. Flow rates were calculated at each step using equations (1), (2) and (5), and a running total -

$$\sum \dot{m}_{p_{\text{out}}} \Delta t$$

was kept. At each step, a check was made to ensure that the ullage had not become saturated and that a negative value was not being used for  $\dot{m}_{\text{evap}}$ .

7. As soon as the ullage became saturated with propellant vapor, the finite difference procedure was terminated. The remainder of the fast fill was analyzed using equations (1) through (6) with

$$\dot{m}_{\text{evap}} = 0.$$

In this case the equations are readily solved analytically, and numerical methods are not required.

8. Following the completion of the fast fill, the slow fill was analyzed. For the 640 gallon tanks, this simply amounted to changing the value of  $\dot{Q}_{\text{in}}$  and proceeding as before. For the 125 gallon tanks, an isentropic portion was calculated using equations (11), (12), (13a) and (13b), after which the last stage of venting was analyzed as described in steps 6 and 7,

$$\begin{aligned} \text{with } p &= 20116 \text{ lbf/ft}^2 \\ T &= T_2 \text{ (just calculated)} \\ \dot{Q}_{\text{in}} &= 2 \text{ gal/min} \end{aligned}$$

and starting with  $V = V_2$ , the value found for the isentropic compression.

The results for total propellant vent masses are summarized in Figures 1 and 2. More detailed results, including a listing of the computer program, are presented in the Appendix.

#### 4. Discussion of Results

No attempt was made to select realistic values of  $A$ , which will depend on the liquid propellant surface area and hence will vary with time, especially in the case of a spherical tank. The results varied with  $A$  throughout the range of values of  $A$  that were investigated. It is likely that realistic values of  $A$  will fall within this range; however, a more thorough study would be required to define the vent masses with a high degree of certainty.

Two other shortcomings of the analysis should be pointed out:

1. Some discrepancies exist in the way  $V$ ,  $m_p$ , and  $\dot{m}_{\text{sat}}$  are handled in the first time step.
2. The slow fill analysis for the 640 gallon tanks does not allow for the possibility that the ullage might not be saturated.

It should be emphasized that this analysis was intended only as a "second approximation," and was a fast-reaction exercise of very limited duration. We did not have time or funding, at the time this work was done, to refine the analysis beyond the point where consistent and reasonably reliable results were being obtained. Our approach and results, including emphasis on the deficiencies of the analysis, are presented here since we are not aware of the existence of anything better, and for the benefit of anyone who might wish to develop this computer code further.

Figures 1 and 2 are cross-plots of the total amounts vented for each tank versus  $A$ . Figure 1 in particular indicates that the propellant mass vented might well grow without bound as the evaporation rate increases. At these high values of propellant vapor mass however, it would be necessary to take account of cooling due to evaporation; this cooling would reduce the vapor pressure and hence the amount evaporated. In addition, we should remember that these high values occur as a result of the very rapid evaporation at early values of time, accompanied by an assumed instantaneous diffusion throughout the tank, with the result that large amounts of propellant are lost out the vent before the gas is saturated. A final consideration: examination of the computer output shows that the curves would stop rising at only slightly higher values of  $A$  than those calculated because of the limitations represented by equations (10') and (10'').

With these considerations in mind, it was decided to select the approximate inflection points in the two curves to estimate the total vent quantities:

$$125 \text{ gallon } \text{N}_2\text{O}_4 \text{ tank: } m_{p.v.} = 4.5 \text{ lbm}$$

$$640 \text{ gallon } \text{N}_2\text{O}_4 \text{ tank: } m_{p.v.} = 24.0 \text{ lbm}$$

The 640 gallon figure corresponds to a higher value of  $A$  than the 125 gallon figure, which is appropriate since  $A$  should be proportional to surface area.

These values are 18.5% and 23.4% greater, respectively, than those obtained with the first approximation. They are also 5 - 10% smaller than the maximum values calculated.

The complete flowrate history (hypergol vapor vent flow rate versus time) calculated by this program is presented in Figure 3.

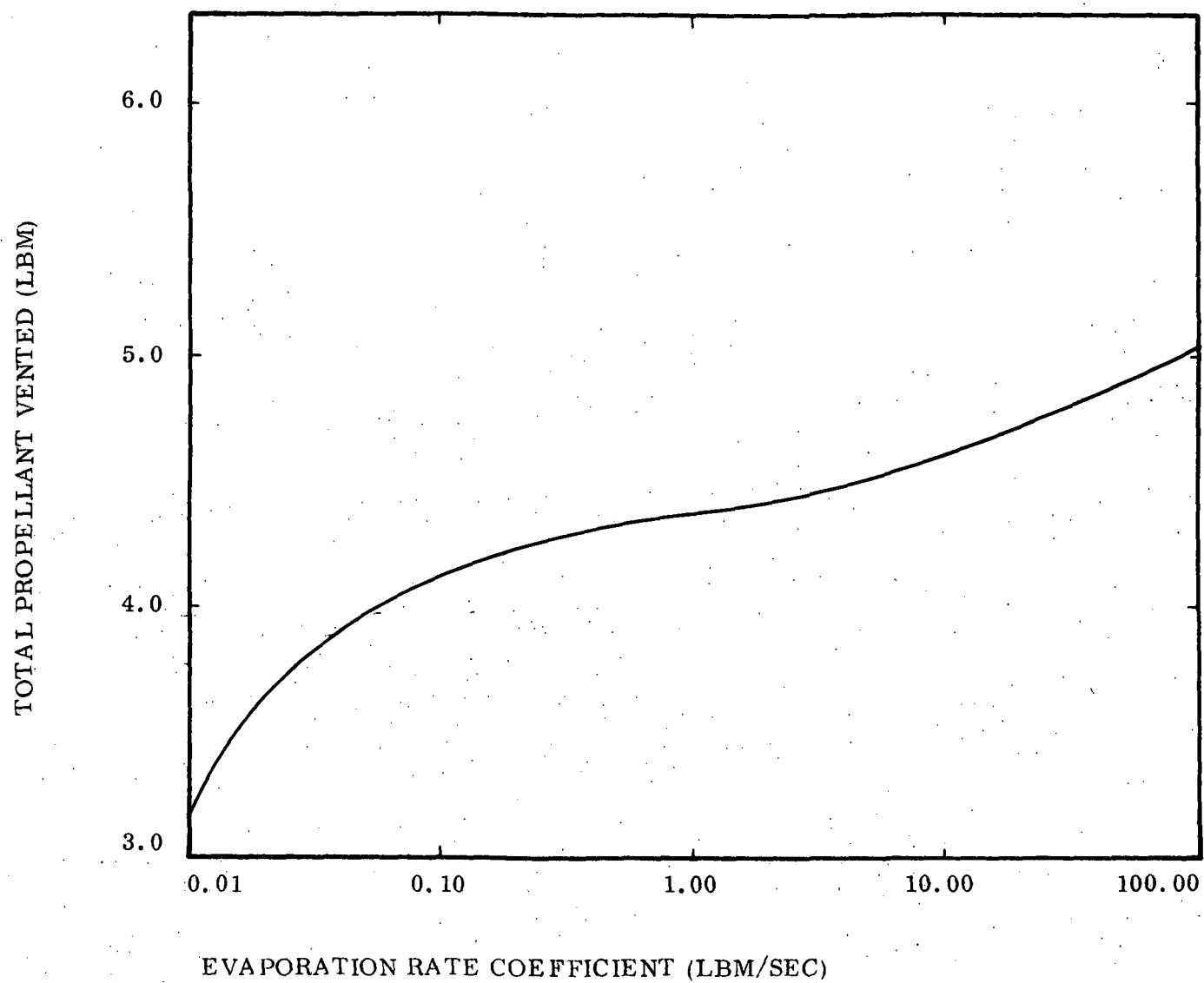


Figure 1:  $\text{N}_2\text{O}_4$  vent mass, 125 gallon tank

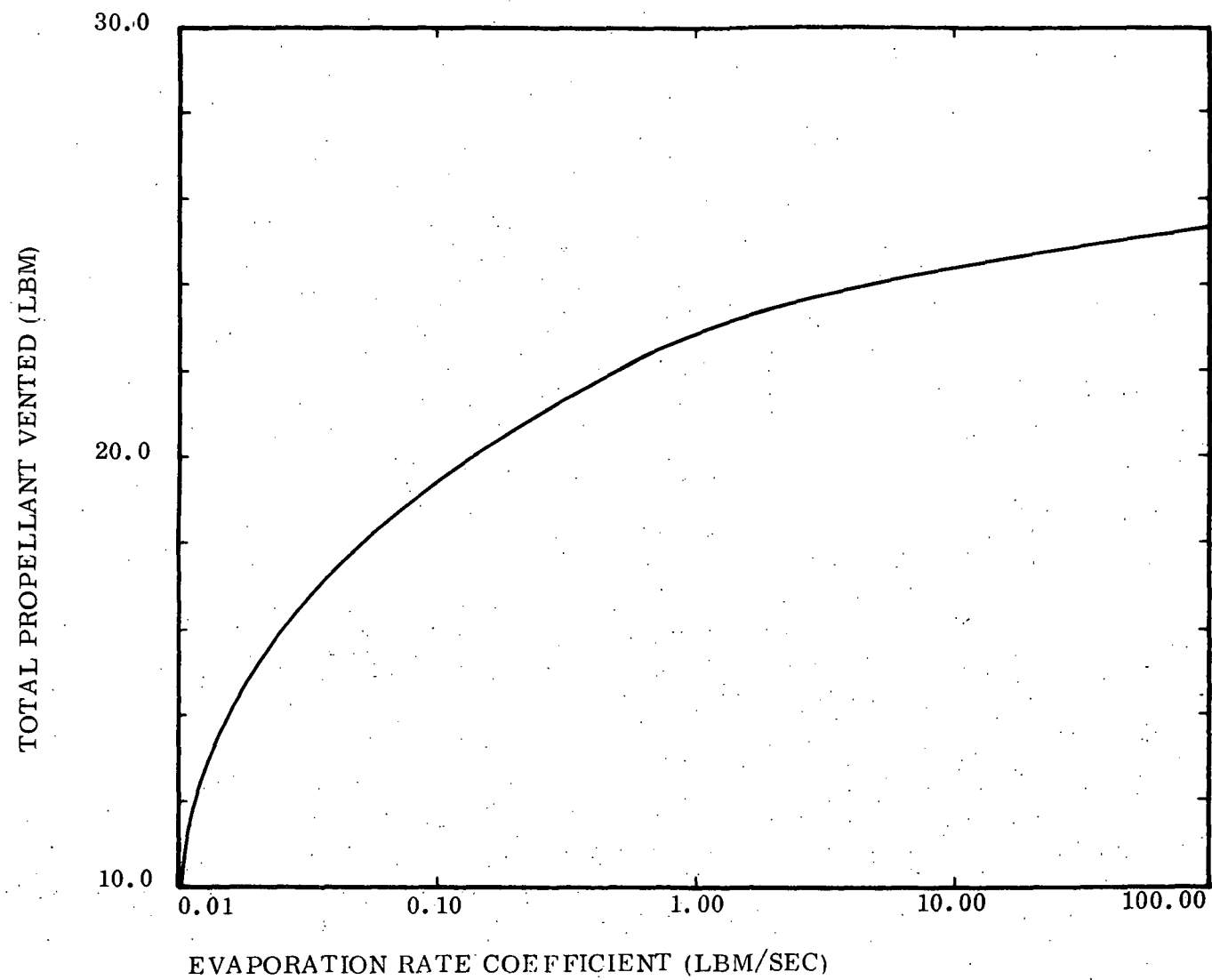


Figure 2.:  $\text{N}_2\text{O}_4$  vent mass, 640 gallon tank

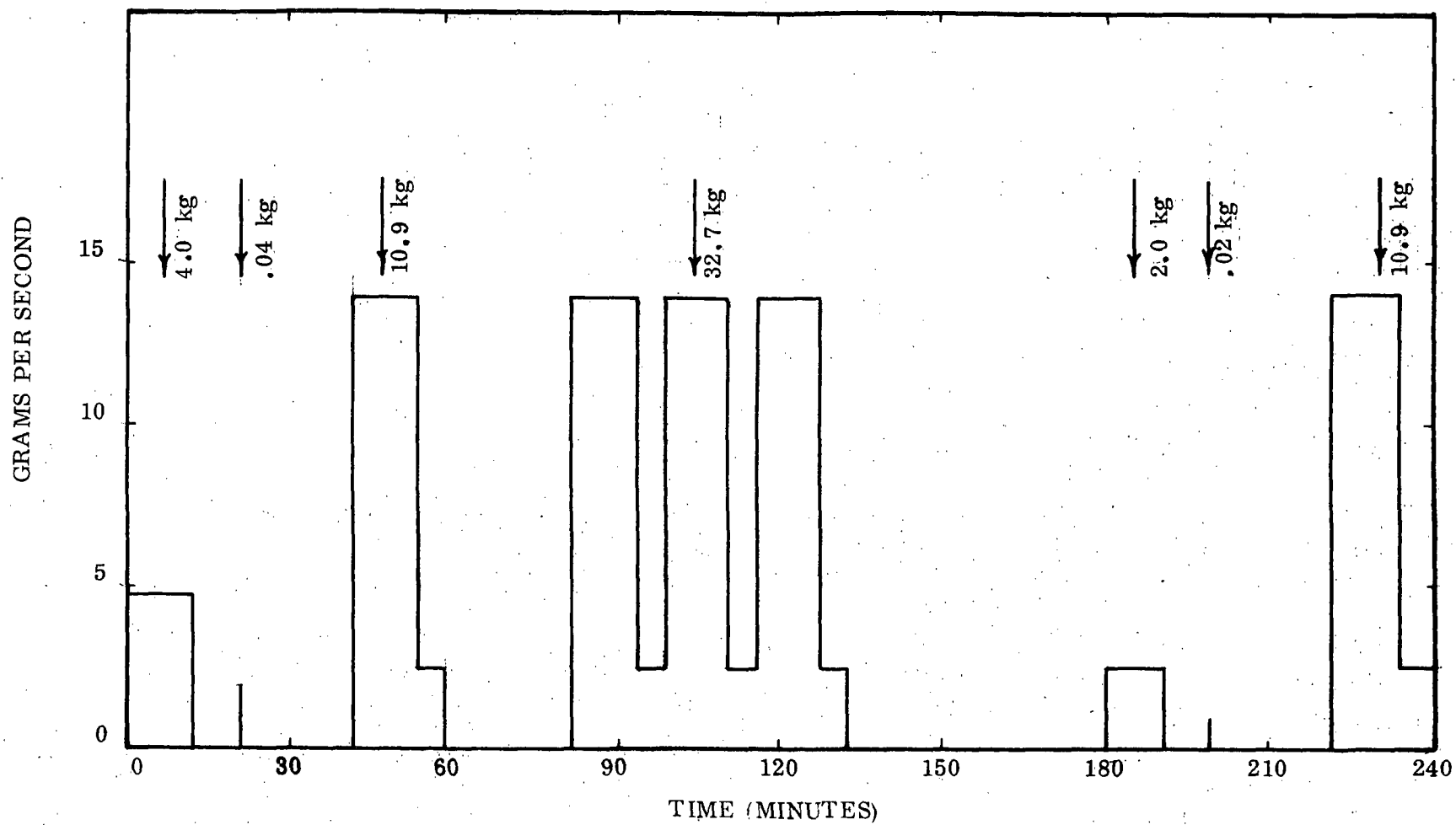


Figure 3: Baseline Flowrate History,  $N_2O_4$  -  $NO_2$  vapors vented during pad servicing operations - does not include helium flow



APPENDIX  
VENT FLOW RATE PREDICTIONS FOR LC-39  
(NORMAL OPERATING CONDITIONS)

This Appendix includes a listing of the computer program used for these calculations, and results for selected values of the "evaporation rate coefficient,"  $A$ , defined in Section 3.1.

```

      DIMENSION A(5),V0(4),RHC(2),PSAT(2),R(2),TITLE(10),QDOTJ(4),
1 VTOT(4),CP(4)
      IN=5
      IOUT=6
      READ (IN,1) (A(I),I=1,5),(V0(J),J=1,2)
      READ (IN,3) (VTOT(J),J=1,2)
      READ (IN,3) (QDOTJ(J),J=1,4)
      READ (IN,3) (CP(K),K=1,2)
3  FORMAT (8F10.3)
      T=529.67
      PMIX=7156.
      PMIX2=20116
      DELT=1.
      RHO(1)=54.8
      RHO(2)=90.35
      PSAT(1)=111.456
      PSAT(2)=2118.24
      R(1)=33.536
      R(2)=17.597
      DO 100 K=1,2
      READ (IN,2) (TITLE(L),L=1,9)
      WRITE (IOUT,10) (TITLE(J),J=1,9)
      DO 100 J=1,2
      WRITE (IOUT,11) V0(J)
      DO 100 I=1,5
      WRITE (IOUT,12) A(I)
      WRITE (IOUT,14)
      TIME=DELT
      KOUNT=1
      AA=A(I)
      ULLAGE=VTOT(J)-.9*V0(J)*.1337
      QDOT=QDOTJ(J)*.1337/60.
      V=VTOT(J)
      EMM=QDOT*DELT*RHO(K)
      EMM2=SQRT(8./9.*AA*PSAT(K)*V*DELT/R(K)/T)
      IF (EMM2.LT.EMM) EMM=EMM2
      EMM2=PSAT(K)*V/R(K)/T
      IF (EMM2.LT.EMM) EMM=EMM2
      FLOW=QDOT+EMM*(R(K)*T/PMIX-1./RHC(K))/DELT
      FLAW=FLOW/.1337
      EFFLUX=FLOW*EMM/V
      SCRUB=EFFLUX*DELT
44  PARA=PSAT(K)*V/EMM/R(K)/T
      IF (PARA.LE.1.) GO TO 66
      EVAP=AA*(PARA-1.)
      TEST=QDOT*RHC(K)
      IF (EVAP.GT.TEST) EVAP=TEST

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DELV=(EVAP/RHC(K)-QDOT)*DEL T
DELM=EVAP*(1.-PSAT(K)/PMIX/PARA)*CELT+EMM/V*DELV
22 TIME=TIME+DEL T
EMM=EMM+DELM
V=V+DELV
PP=EMM*R(K)*T/V
FLOW=QDOT+EVAP*(R(K)*T/PMIX-1./RHC(K))
FLAW=FLOW/.1337
EFFLUX=FLOW+EMM/V
SCRUB=SCRUB+EFFLUX*DEL T
KCUNT=KCUNT+1
IF (KCUNT.LT.10) GO TO 33

VOUT=V/.1337
POUT=PP/144.
WRITE (IOUT,13) TIME,EMM,VCUT,POUT,FLAW,EFFLUX,SCRUB
KCUNT=0
33 IF (V.GT.ULLAGE) GO TO 44
VOUT=V/.1337
POUT=PP/144.
GO TO 88
66 EMM=PSAT(K)*V/R(K)/T
PP=PSAT(K)
VCUT=V/.1337
POUT=PSAT(K)/144.
WRITE (IOUT,13) TIME,EMM,VOUT,POUT,FLAW,EFFLUX,SCRUB
CHEK1=PSAT(K)*ULLAGE/R(K)/T
TIDE=(V-ULLAGE)/QDOT
TIME=TIME+TIDE
VOUT=ULLAGE/.1337
POUT=PSAT(K)/144.
FLAW=QDOT/.1337
EFFLUX=QDOT*PSAT(K)/R(K)/T
SCRUB=SCRUB+EFFLUX*TIDE
CHEK2=EMM-EFFLUX*TIDE
IF (ABS(CHEK1-CHEK2).GT..01*CHEK1) WRITE (IOUT,15)
EMM=CHEK1
88 WRITE (IOUT,13) TIME,EMM,VCUT,POUT,FLAW,EFFLUX,SCRUB
QDOT=QDOT*(J+2)*.1337/60.
ULOLD=ULLAGE
ULLAGE=VTOT(J)-V0(J)*.1337
IF (J.EQ.1) GC TO 99
EMM=PSAT(K)*ULLAGE/R(K)/T
TIDE=V0(J)*.01337/QDOT
TIME=TIME+TIDE
VOUT=ULLAGE/.1337
FLAW=QDOT/.1337
EFFLUX=QDOT*PSAT(K)/R(K)/T
SCRUB=SCRUB+EFFLUX*TIDE
WRITE (IOUT,13) TIME,EMM,VOUT,POUT,FLAW,EFFLUX,SCRUB
GO TO 100
99 WRITE (IOUT,16)
GAMMA=(PP*CP(K)+(PMIX-PP)*5.)/(PP*(CP(K)-1.986)+(PMIX-PP)*3.)
PCW1=1./GAMMA
VISEN=ULOLD*(PMIX/PMIX2)**PCW1
IF (VISEN.LT.ULLAGE) GO TO 100
TIME=TIME+(ULOLD-VISEN)/QDOT
VOUT=VISEN/.1337
PP=PP*PMIX2/PMIX

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POUT=PP/144.
FLAW=0.
EFFLUX=0.
WRITE (IOUT,13) TIME,EMM,VCUT,POUT,FLAW,EFFLUX,SCRUB
WRITE (ICUT,17)
POW2=(GAMMA-1.)/GAMMA
T2=T*(PMIX2/PMIX)**POW2
TIDE=(VISEN-ULLAGE)/QDOT
TIME=TIME+TIDE
VCUT=ULLAGE/.1337
FLAW=QDOT/.1337
EFFLUX=QDOT*PP/R(K)/T2
SCRUB=SCRUB+EFFLUX*TIDE
EMM=EMM-EFFLUX*TIDE
WRITE (IOUT,13) TIME,EMM,VCUT,PCUT,FLAW,EFFLUX,SCRUB
100 CONTINUE
STOP
1 FORMAT (5F10.3/4F10.3)
2 FORMAT (9A4)
10 FORMAT (1H1,9A4)
11 FORMAT (////' FINAL PROPELLANT VOLUME =' ,F6.0,' GALLONS'//)
12 FORMAT (/' EVAPORATION RATE (COEFFICIENT =' ,F7.2,' LBM/SEC'//)
13 FORMAT (F8.0,F11.3,F11.2,F10.3,F11.3,F12.4,F12.3)
14 FORMAT (//3X,'TIME PROPELLANT ULLAGE PARTIAL TOTAL PR
1PROPELLANT',6X,'TOTAL'/3X,'(SEC) VAPOR MASS VOLUME PRESSURE
2 OUTFLOW OUTFLOW PROPELLANTS'/14X,'(LRM) (GAL) (PSIA
3A) (GAL/SEC) (LRM/SEC) VENTED(LBM)'//)
15 FORMAT (' OOPS')
16 FORMAT (' VENT CLOSES')
17 FORMAT (' VENT OPENS')
END

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# $N_2O_4$ RESULTS - 125 GALLON TANK

EVAPORATION RATE CCEFFICIENT = 1.00LBM/SEC

| TIME<br>(SEC)        | PROPELLANT<br>VAPOP MASS<br>(LBM) | ULLAGE<br>VOLUME<br>(GAL) | PARTIAL<br>PRESSURE<br>(PSIA) | TOTAL<br>CUTFLOW<br>(GAL/SEC) | PROPELLANT<br>CUTFLOW<br>(LBM/SEC) | TOTAL<br>PROPELLANTS<br>VENTED(LBM) |
|----------------------|-----------------------------------|---------------------------|-------------------------------|-------------------------------|------------------------------------|-------------------------------------|
| 10.                  | 3.862                             | 132.66                    | 14.095                        | 0.691                         | 0.0201                             | 0.876                               |
| 20.                  | 3.952                             | 131.01                    | 14.626                        | 0.234                         | 0.0071                             | 0.984                               |
| 30.                  | 3.927                             | 129.35                    | 14.698                        | 0.176                         | 0.0053                             | 1.043                               |
| 40.                  | 3.879                             | 127.68                    | 14.708                        | 0.168                         | 0.0051                             | 1.094                               |
| 50.                  | 3.829                             | 126.01                    | 14.710                        | 0.167                         | 0.0051                             | 1.145                               |
| 58.                  | 3.788                             | 124.68                    | 14.710                        | 0.167                         | 0.0051                             | 1.186                               |
| 677.                 | 0.652                             | 21.46                     | 14.710                        | 0.167                         | 0.0051                             | 4.322                               |
| VENT CLOSES<br>1032. | 0.652                             | 9.65                      | 41.351                        | 0.000                         | 0.0000                             | 4.322                               |
| VENT OPENS<br>1052.  | 0.605                             | 8.96                      | 41.351                        | 0.033                         | 0.0023                             | 4.369                               |

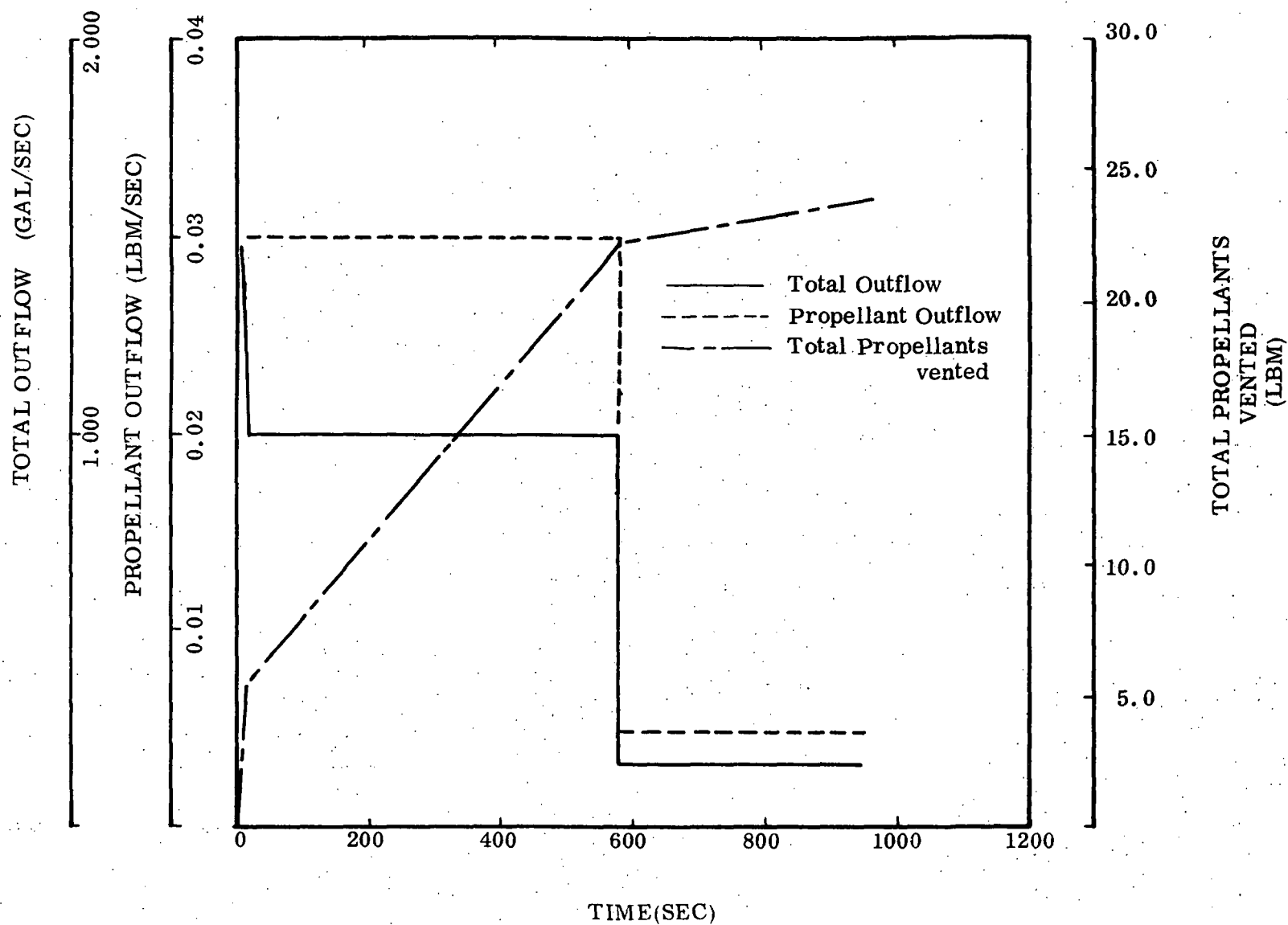
# $N_2O_4$ RESULTS 640 GALLON TANK

EVAPORATION RATE COEFFICIENT = 10.00LBM/SEC

| TIME<br>(SEC) | PROPELLANT<br>VAPOR MASS<br>(LBM) | ULLAGE<br>VOLUME<br>(GAL) | PARTIAL<br>PRESSURE<br>(PSIA) | TOTAL<br>OUTFLOW<br>(GAL/SEC) | PROPELLANT<br>OUTFLOW<br>(LBM/SEC) | TOTAL<br>PROPELLANTS<br>VENTED(LBM) |
|---------------|-----------------------------------|---------------------------|-------------------------------|-------------------------------|------------------------------------|-------------------------------------|
| 10.           | 20.029                            | 661.26                    | 14.663                        | 1.477                         | 0.0447                             | 5.112                               |
| 20.           | 19.788                            | 651.27                    | 14.709                        | 1.006                         | 0.0306                             | 5.441                               |
| 30.           | 19.485                            | 641.27                    | 14.710                        | 1.000                         | 0.0304                             | 5.746                               |
| 31.           | 19.455                            | 640.27                    | 14.710                        | 1.000                         | 0.0304                             | 5.776                               |
| 578.          | 2.838                             | 93.41                     | 14.710                        | 1.000                         | 0.0304                             | 22.392                              |
| 962.          | 0.894                             | 29.41                     | 14.710                        | 0.167                         | 0.0051                             | 24.337                              |

Slow fill commences at 578 sec, ends at 962 sec.

640 GAL. TANK,  $N_2O_4$ , EVAPORATION RATE COEFFICIENT =  $10.0 \frac{\text{lbm}}{\text{sec}}$



125 GAL. TANK,  $N_2O_4$ , EVAPORATION RATE COEFFICIENT =  $1.00 \frac{\text{lbm}}{\text{sec}}$

